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(54) Converter circuit employing pulse-width modulation

(57) A voltage conversion and regulation system uses pulse-width modulation to vary the periodic energization of a tuned circuit 21 employed to drive a transformer and an associated rectifier. The tuned resonant circuit is periodically energized from a DC source at a fixed rate but for alterable periods of time during each cycle so as to produce in the tuned circuit an alternating current of fixed frequency for subsequent transformation and rectification into a DC voltage of predetermined, regulated level. A pulse-width modulator 42 is connected in feedback-loop fashion between the system output terminals and switch means 26, 28 employed to effect the periodic energization. Varying the length of time during which the switch means are activated in response to changes in the level of output voltage produces the desired regulating control.

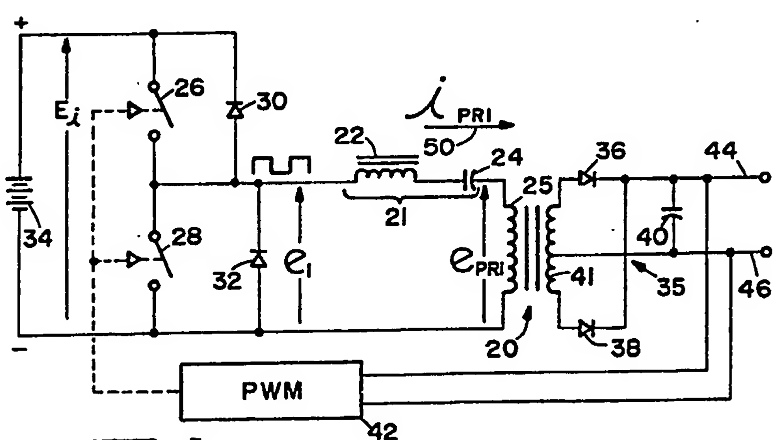

Fig 1.

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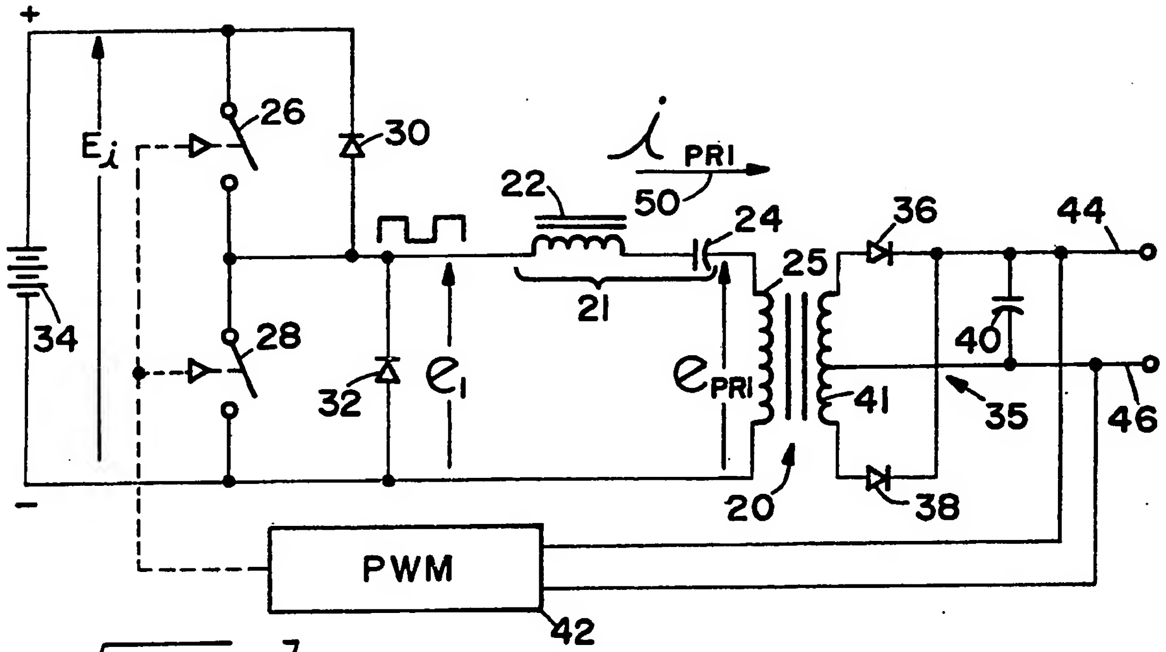

Fig 1

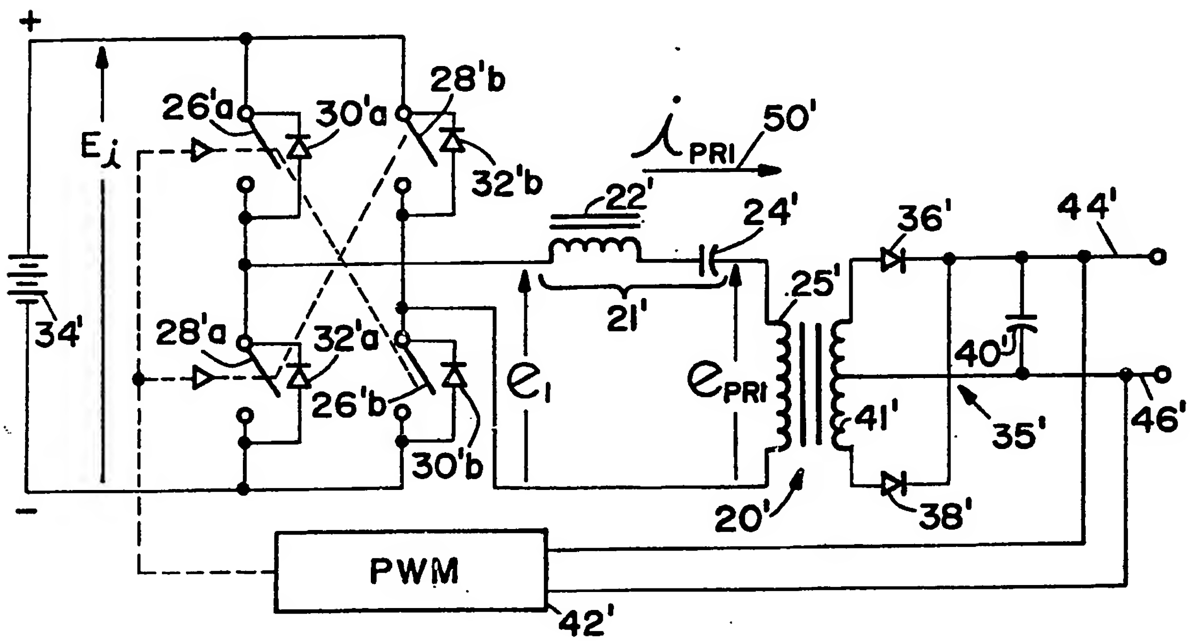

Fig 4

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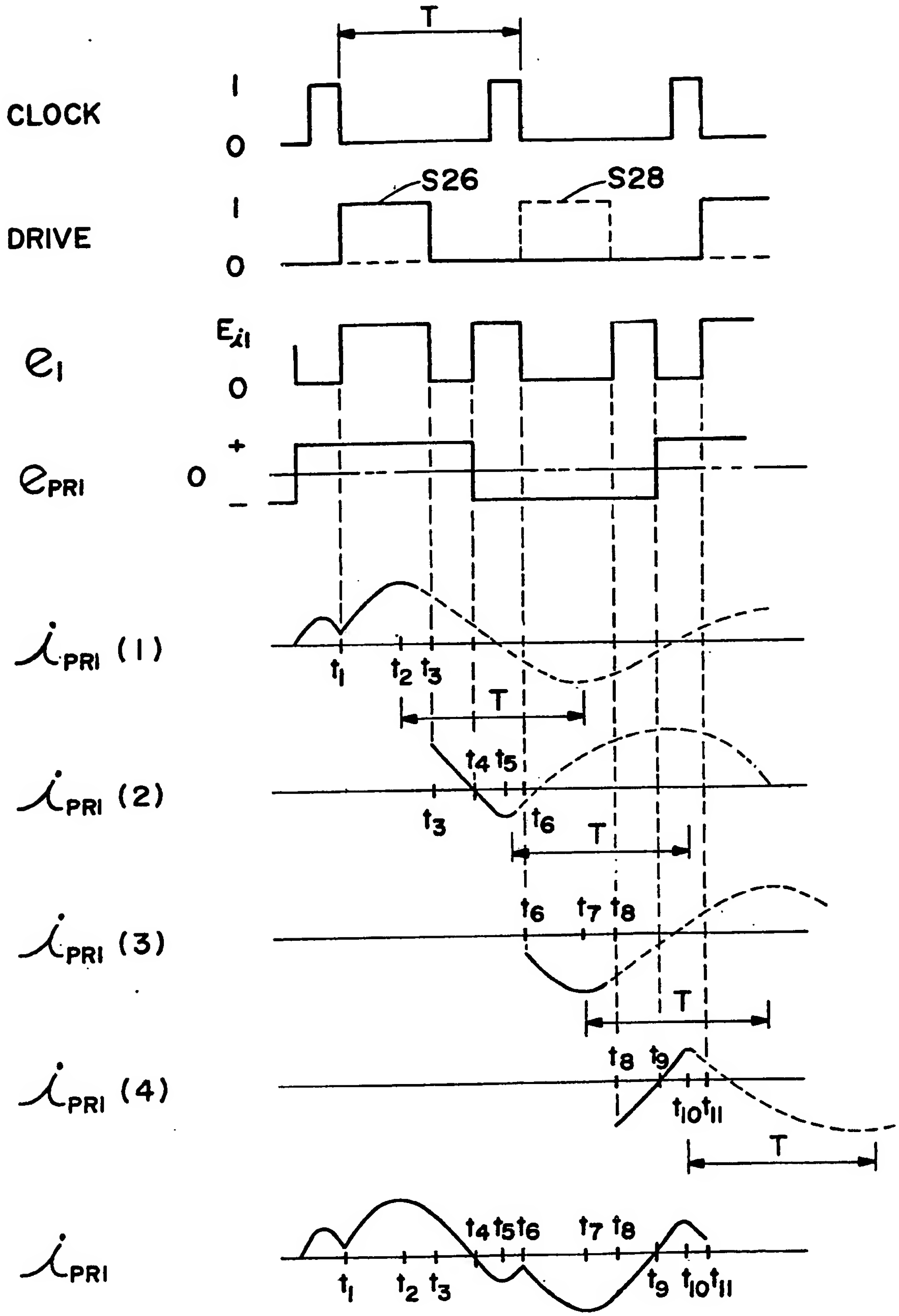

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i_{PRI} (4)
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Fig 2

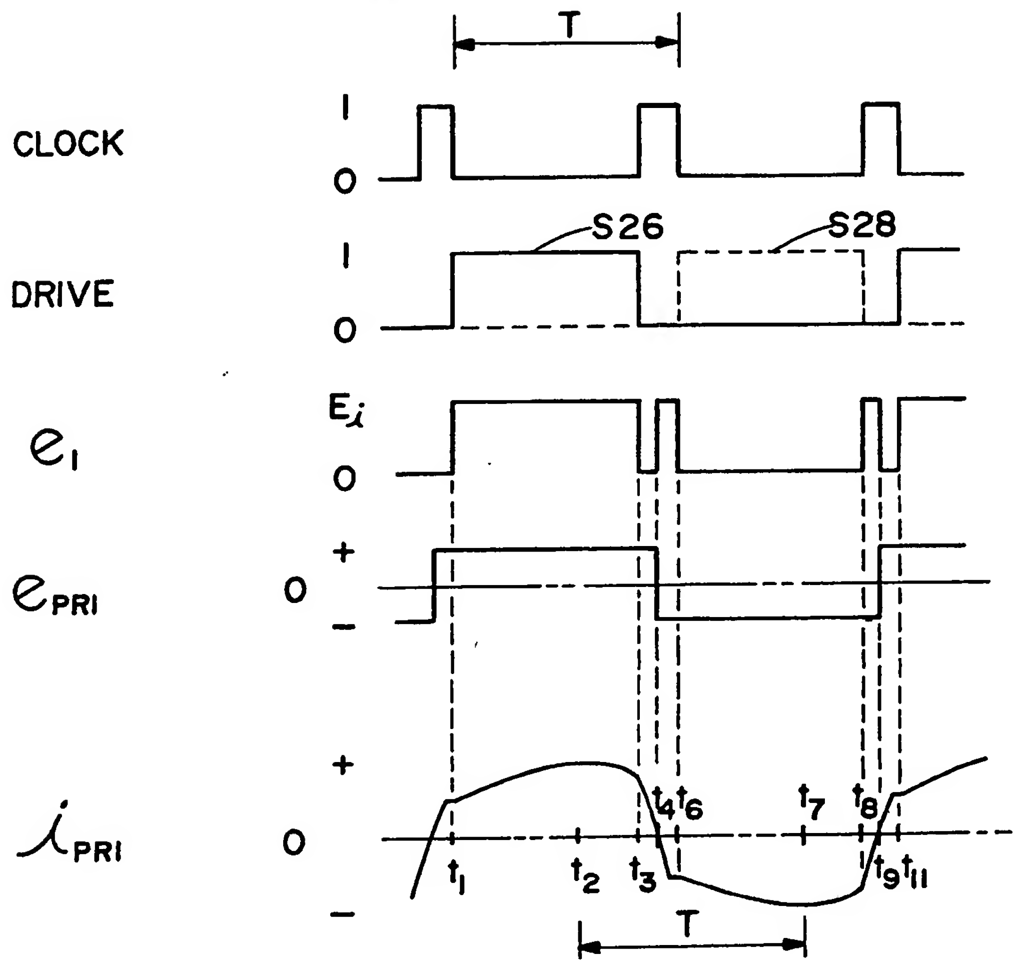
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Fig 3.

SPECIFICATION

Converter circuit employing pulse-width modulation

Background of the Invention

The subject matter of the present invention pertains to a circuit and method of same for converting and regulating a DC voltage via the selective and periodical energization of a tuned resonant circuit. Pertinent examples of such circuits include those disclosed in Schwarz U.S. Patent No. 3,953, 779, an article entitled "A 95 Percent Efficient 1kW DC Converter with an Internal Frequency of 50kHz" by F. C. Schwarz and J. B. Klassens of the Power Electronics Laboratory of the Department of Electrical Engineering, State University of Technology, Delft, The Netherlands, and Andrews U.S. patent No. 3,596,165, the latter of which is assigned to the assignee of the present invention. Such circuits operate, basically, by periodically energizing a resonant circuit from a source of direct current so as to produce in the tuned circuit an alternating current, and then transforming the alternating current to a level producing, upon rectification, a desired DC potential. Limited regulation may also be obtained by altering the energization rate in accordance with changes in the input supply or output demand.

In both the Schwarz and Andrews circuits, the tuned elements are energized at a rate offset a variable distance from resonance to effect both conversion and regulation. A disadvantage of such circuits is that their regulating capability is limited to a load range of about 2 to 1; that is, from about one-half load to about full load.

Summary of the Invention

The present invention is directed to a converter circuit and method of same for converting and regulating a DC voltage over a wide range of variation in either the input supply or the output demand. More particularly, the circuit of the present invention comprises a converter circuit similar in many respects to that disclosed by the Andrews reference cited in an earlier part of this specification, except that the operation of the circuit is controlled by pulse-width modulation rather than frequency modulation.

The circuit of the present invention includes a tuned resonant circuit, switch means for periodically energizing the circuit from a source of direct current so as to produce in the circuit an alternating current having a constant frequency substantially equal to the resonant frequency of the circuit, output means for producing an output in response to the alternating current, and a pulse-width modulator for altering the duration of each periodic energization depending on the level of the output. The tuned circuit comprises an inductor and capacitor connected in series with the primary winding of an output transformer, the secondary winding of which is connected in turn to a conventional diode-capacitor rectifier circuit to produce an ultimate DC output. During operation, as the level of input supply or output demand changes so as to affect the level of the circuit output, the pulse-width modulator operates to increase or decrease the duration of periodic energization of the tuned circuit in a manner tending to maintain the output at a constant regulated level. As indicated earlier, with the exception of the use of pulse-width modulation to control the circuit energization, the circuit of the present invention is similar in many respects to that disclosed by the Andrews reference.

The principal advantages of the circuit and method of the present invention are their simplicity of understanding and maintenance and their ability to maintain efficient voltage regulation over a relatively wide range of variation in input and output levels; in particular, over a range greater than that capable of being handled by the Andrews circuit.

It is, therefore, a principal objective of the present invention to provide a circuit and method of same for converting and regulating a DC voltage over a wide range of variation of input supply and output demand.

It is a feature of the present invention that effective voltage conversion and regulation are accomplished via a tuned resonant circuit, the resonant elements of which are periodically energized from a DC source at a predetermined constant rate, but for periods of varying duration depending on input supply and output demand.

The foregoing objectives, features, and advantages of the present invention will be more readily understood upon consideration of the following detailed description of the invention taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

FIG. 1 is a simplified schematic representation of an exemplary embodiment of the converting and regulating circuit of the present invention.

FIGS. 2 and 3 are each a series of waveforms illustrating the operation of the circuit of FIG. 1.

FIG. 4 is a simplified schematic representation of an alternate embodiment of the converting and regulating circuit of the present invention.

Detailed Description of the Preferred Embodiment

Referring to FIG. 1, there is disclosed in simplified schematic form an exemplary embodiment of the converting and regulating circuit of the present invention including: an inductor 22 and capacitor 24, defining in combination a tuned resonant circuit 21, connected in series with the primary winding 25 of an output transformer 20, the secondary winding 41 of which is coupled to a pair of output terminals 44, 46 via a conventional diode-capacitor rectifier arrangement; switch means 26 and 28 and a respective pair of parallel-connected diodes 30 and 32 for selectively energizing the tuned circuit 21 and transformer winding 25 from a source 34 of direct current; and a pulse-width modulator 42 connected between the output

terminals 44, 46 and the switch means 26, 28 for controlling the operation of the switch means in a manner described more fully below. The two switch means 26, 28 may be of any suitable design permitting rapid switch rates in the area of 25 kHz, and electronic control. An example of such means is the transistor arrangement disclosed by the Andrews reference cited in an earlier part of this specification. Similarly, the pulsewidth modulator 42 may be any suitable unit capable of controlling the on and off states of the two switch means according to a voltage level present at the two terminals 44, 46. An example of such a unit is that marketed under the designation 3524 by such manufacturers as Silicon General and Texas Instruments.

In operation, the pulse-width modulator 42 alternately activates the two switch means 26, 28 in a manner producing in the tuned circuit 21 and transformer winding 25 an alternating current of magnitude and periodic duration sufficient to produce at the output terminals 44, 46, after transformation by the transformer 20 and subsequent rectification, a DC potential of predetermined, regulated magntidude. A more detailed understanding of the circuit of FIG. 1 is obtained upon consideration of the waveforms of FIGS. 2 and 3 wherein the curve labeled CLK defines a clock signal (with each pair of adjacent pulses representing a single cycle) for referencing the timed operation of the pulse-width modulator 42, the curve labeled DRIVE represents the ON/OFF state of the two switch means 26, 28, the curve labeled e_1 represents the voltage impressed across the circuit defined by the tuned circuit 21 and the transformer winding 25 during operation of the switch means, and the curves labeled e_{pri} and i_{pri} represent the voltage and current, respectively, developed in the primary winding alone. The four curves of FIG. 2 labeled $i_{pri(1)}$ through $i_{pri(4)}$ are component segments of the i_{pri} curve that have been separated for purposes of illustration. Each of the voltage and current curves are related by a series of dashed lines and timing marks t_1 through t_{11} to indicate the occurence of significant events during their generation. An arrow labeled T is included to indicate the relationship of a half cycle of the CLK curve to the periodicity of the remaining curves in the figures. For simplicity, the inductor 22 and capacitor 24 forming the tuned circuit 21 are assumed to be purely reactive and the primary winding 25 is considered to be primarily a resistance in parallel with a diode-coupled capacitance. Note that, in the DRIVE curve of FIGS. 2 and 3, the solid line labeled S26 represents the state of switch means 26 and the dashed line labeled S28 represents the state of switch means 28, with a high level in each case indicating a closed or ON state and a low level indicating an open or OFF state. Note also that switch means 26 and 28, while potentially open at the same time, are never permitted to be closed at the same time as such a condition would effectively short circuit the input source 34.

Assume as a starting point that, at a time just before time t_1, switch means 26 and 28 are open, as indicated by the drive curve of FIG. 2, and current i_{pri} is flowing in a positive direction, as indicated by the arrow 50 in FIG. 1, through the circuit defined by the inductor 22, the capacitor 24, the transformer primary winding 25 and the forward-biased diode 32, the source of the current i_{pri} being release of a charge stored in the capacitor 24 during a previous operation of the circuit. At time t_1, the pulse-width modulator 42 operates to close switch means 26, as indicated by the DRIVE curve of FIG. 2, and cause the voltage E_i of the DC source 34 to be impressed across the tuned circuit 21 and primary winding 25, as indicated by the e_1 curve. This causes the current i_{pri} to increase sharply in the positive direction, as indicated by the $i_{pri(1)}$ curve, until reaching a maximum at time t_2 and then decrease in accordance with the typical transient response of a series LC circuit to a step wave. (It is assumed herein that the reader is familiar with the typical transient response of such an LC circuit to step functions of both the positive and negative kind.) Note that the diode 32 is reverse-biased by the application of the source voltage E_i and the path for the current i_{pri} is now through the source 34. If switch means 26 were left closed, the current i_{pri} would oscillate about zero at the resonant frequency of the LC circuit while damping exponentially as indicated by the dotted-line portion of the $i_{pri(1)}$ curve.

At time t_3, though switch means 26 is opened and the source voltage E_i removed from the circuit. The current i_{pri}, however, rather than falling to zero, is maintained for a short time by the collapsing field of the inductor 22 and caused to continue flowing through the circuit once again including the now forward-biased diode 32 until reaching zero at time t_4. At that time, the field of the inductor 22 is dissipated and the capacitor 24, charged to a maximum potential greater than that of the source 34 drives the current i_{pri} in a reverse direction, past the again reverse-biased diode 32 and through the forward-biased diode 30, back into the source 34 itself. This phenomenon is indicated by a comparison of the curves of FIG. 2 labeled e_1 and $i_{pri(2)}$. (It will be recalled that high Q tuned LC circuit driven at its resonant frequency will produce a voltage across the capacitor with a peak value about Q times the driving voltage; that is, for $E_i = 300$ volts and $Q = 10$, the voltage across capacitor will be about 3000 volts as a first approximation.)

As the charge on the capacitor 24 dissipates, the current i_{pri} increases in magnitude until reaching a maximum at time t_5 when it begins to decrease again toward zero. If the circuit were left undisturbed, the current i_{pri} would decrease to zero and then resume flowing in the positive direction through the then forward-biased diode 32, as indicated by the dotted-line portion of the curved $i_{pri(2)}$, until dissipating to zero.

At time t_6, switch means 28 is closed and the current i_{pri} flowing in the reverse direction through the source 34 is suddenly shunted

through the zero resistance of the swithc means. This causes the magnitude of the current i_{pri}, as indicated in the curve labeled $i_{pri(3)}$, to increase suddenly, still in the reverse direction, until peaking at time t_7 and then decreasing toward zero. As before, if switch means 28 was left closed, the current i_{pri} would oscillate about zero in typical transient response to the removal of a step wave from a series LC circuit. However, at time t_8, switch means 28 is again opened and the current i_{pri}, maintained for a short time again by the collapsing field of the inductor 22, is forced a second time through the forward-biased diode 30 and into the source 34 until dropping to zero at time t_9 when the capacitor 24, charged now to its maximum negative potential by the previously flowing reverse current, begins to discharge and drive the current again in the forward direction, as indicated by the curve labeled $i_{pri(4)}$, through the diode 32. As the charge on the capacitor 24 dissipates, the current i_{pri} reaches a maximum at time t_{10} and then begins to decrease until time t_{11} when switch means 26 is again closed and the process is repeated.

As mentioned earlier, the four current segments $i_{pri(1)}$ through $i_{pri(4)}$ forrn in combination the current i_{pri} actually flowing through the transformer winding 25 of the transformer 20. Although the current i_{pri} is somewhat sinusoidal in nature, the voltage e_{pri} developed across the primary winding 25 follows essentially the curve of a square wave primarily because of the load employed in the circuit wherein diodes 36 and 38 operate to charge capacitor 40. For an entirely resistive AC load, the voltage e_{pri} would be less a square wave and more like the sinusoid of the current i_{pri}.

Control of the two switch means 26, 28 to achieve the above-described operation is obtained via the pulse-width modulator 42 connected between the output terminals 44, 46 of the circuit and the two switch means. During normal quiescent operation, the pulse-width modulator 42 produces a series of pulses, such as those depicted by the DRIVE curve of FIG. 2, at a constant rate, preferably equal to the resonant frequency of the tuned circuit 21, and with a width or periodic duration sufficient to cause each switch means 26, 28 to be closed for about 30% of each operating cycle, defined as indicated earlier by two cycles of the CLK curve, and open for the remainder of the cycle. Each time the output level of the DC voltage produced by the circuit is disturbed, such as by a change in either the output demand or the input supply, the pulse-width modulator 42 automatically varies the width of the individual pulses forming the pulse stream controlling the operation of the two switch means 26, 28.

For example, if the output voltage at the terminals 44, 46 decreases, for example in response to an increase in output demand, the pulse-width modulator 42 will operate to increase the width of the pulses in the pulse stream. Such an occurrence is shown by the curves of FIG. 3, individual ones of which are labeled to match corresponding curves of FIG. 2. As shown in FIG. 3, the frequency of the pulse stream is maintained equal to that of FIG. 2, but the width or time duration of each pulse is increased significantly. As a result, the current i_{pri}, produced in the same manner as discussed earlier, rises to an increased magnitude and encloses a larger area under its curve. Correspondingly, the output voltage across the two terminals 44, 46 is also increased. The increase in pulse-width is limited by feedback-loop operation of the pulse-width modulator 42 to an amount just sufficient to raise the output voltage of the circuit to its previous undisturbed level.

If instead, the output voltage is increased, such as by an increase in the input supply or a decrease in the output demand, the width of the DRIVE curve pulses will be narrowed below those of FIG. 2 to produce a decreased current i_{pri} in the transformer primary and a corresponding decrease in the voltage produced at the output terminals. At very low load demand, the operation of the circuit of FIG. 1 actually becomes discontinuous with the pulses of the drive curve having a width just sufficient to maintain an alternating charge on the capacitor 24.

In practice, very little change in pulse width is required to compensate for changes in output voltage caused by a variation in output demand as most of the change is due to a variation in input supply.

Typical values for the various components of the circuit of FIG. 1 include an inductor 22 of 0.4 millihenry, a capacitor 24 of 0.1 microfarad, a transformer 20 having a magnetizing inductance of around 400 millihenry, and a capacitor 40 of 5,000 microfarads. Typical operating voltages include an input voltage of around 300 volts and an output voltage of around 100 volts, the difference being due primarily to the turns ratio of the transformer 20. The preferred operating frequency would be the approximately 25 kHz resonant frequency of its tuned circuit 21. Such a circuit is capable of providing a regulated output for input voltages in the range from about 270 volts to about 500 volts and output demands in the range from about zero to about full rated load.

Referring briefly to the circuit of FIG. 3, there is disclosed a full-wave equivalent of the circuit of FIG. 1. For ease of correlation, the elements of the circuit of FIG. 4 are labeled to match those of the circuit of FIG. 1 except for the use of distinguishing prime marks. The operation of the circuit of FIG. 3 is similar in most respects to that of FIG. 1 and will be readily understood by those persons familiar with the art. The major difference in the voltage and current curves produced by the operation of such circuit is that the input voltage curve e_1 alternates between $+E_i$ and $-E_i$, rather than $+E_i$ and zero as before. Otherwise, the curves of FIGS. 2 and 3 apply to the circuit of FIG. 4 except for changes in magnitude due to the full-wave versus half-wave characteristics of the circuit.

Accordingly, there has been disclosed an energy converting and regulating circuit operating by pulse-width modulation to produce a DC

voltage of predetermined, regulated magnitude.

The terms and expressions which have been used in the foregoing specification are used therein as terms of description and not of limitation, and there is no intention, in the use of such expressions, of excluding equivalents of the features shown and described or portions thereof, it being recognized that the scope of the invention is defined and limited only by the claims which follow.

CLAIMS

1. An energy converting and regulating circuit comprising:

(a) a tuned circuit;

(b) means for periodically energizing said tuned circuit from a source of direct current so as to produce in said tuned circuit an alternating current of constant frequency;

(c) means coupled to said tuned circuit for receiving an output in response to said alternating current; and

(d) means responsive to said output for altering the duration of each periodic energization of said tuned circuit depending on the level of said output.

2. The energy converting and regulating circuit of claim 1 wherein said means (b) includes switch means for selectively connecting said tuned circuit to said source of direct current, and wherein said means (d) includes means coupled to said switch means for maintaining each said connection for a period of time depending on the level of said output.

3. The energy converting and regulating circuit of claim 1 wherein said means (d) includes means for increasing the duration of each period energization of said tuned circuit in response to a decrease in the level of said output.

4. The energy converting and regulating circuit of claim 1 wherein said means (d) includes means for decreasing the duration of each periodic energization of said tuned circuit in response to an increase in the level of said output.

5. An improved energy converting and regulating circuit of the type including a tuned circuit, means for periodically energizing said tuned circuit from a source of direct current so as to produce in said circuit an alternating current, means coupled to said tuned circuit for receiving an output in response to said alternating current, and means responsive to said output for altering the periodic energization of said tuned circuit depending on the level of said output, wherein the improvement comprises means for causing said energization of said tuned circuit to occur at a fixed rate so as to produce in said circuit an alternating current of constant frequency and means for causing the duration of each periodic energization to increase with a decrease in the level of said output and decrease with an increase in the level of said output.

6. An energy converting and regulating process comprising the steps of:

(a) providing a tuned circuit;

(b) periodically energizing said tuned circuit from a source of direct current so as to produce in said circuit an alternating current of constant frequency;

(c) receiving an output in response to said alternating current produced in said tuned circuit; and

(d) responsive to said output, altering the duration of each periodic energization of said tuned circuit depending on the level of said output.

7. The energy converting and regulating process of claim 6 wherein said step (b) includes selectively connecting said tuned circuit to said source of direct current, and wherein said step (d) includes maintaining each said connection for a period of time depending on the level of said output.

8. The energy converting and regulating process of claim 6 wherein said step (d) includes increasing the duration of each periodic energization of said tuned circuit in response to a decrease in the level of said output.

9. The energy converting and regulating process of claim 6 wherein said step (d) includes decreasing the duration of each periodic energization of said tuned circuit in response to an increase in the level of said output.

10. An energy converting and regulating circuit substantially as hereinbefore described with reference to Figures 1 to 3 or Figure 4 of the accompanying drawings.

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